Nuclear Interactions at Ultra-High Energies in Light of Recent Auger Results

A summary of the February, 2008 Workshop at the Institute for Nuclear Theory, University of WA

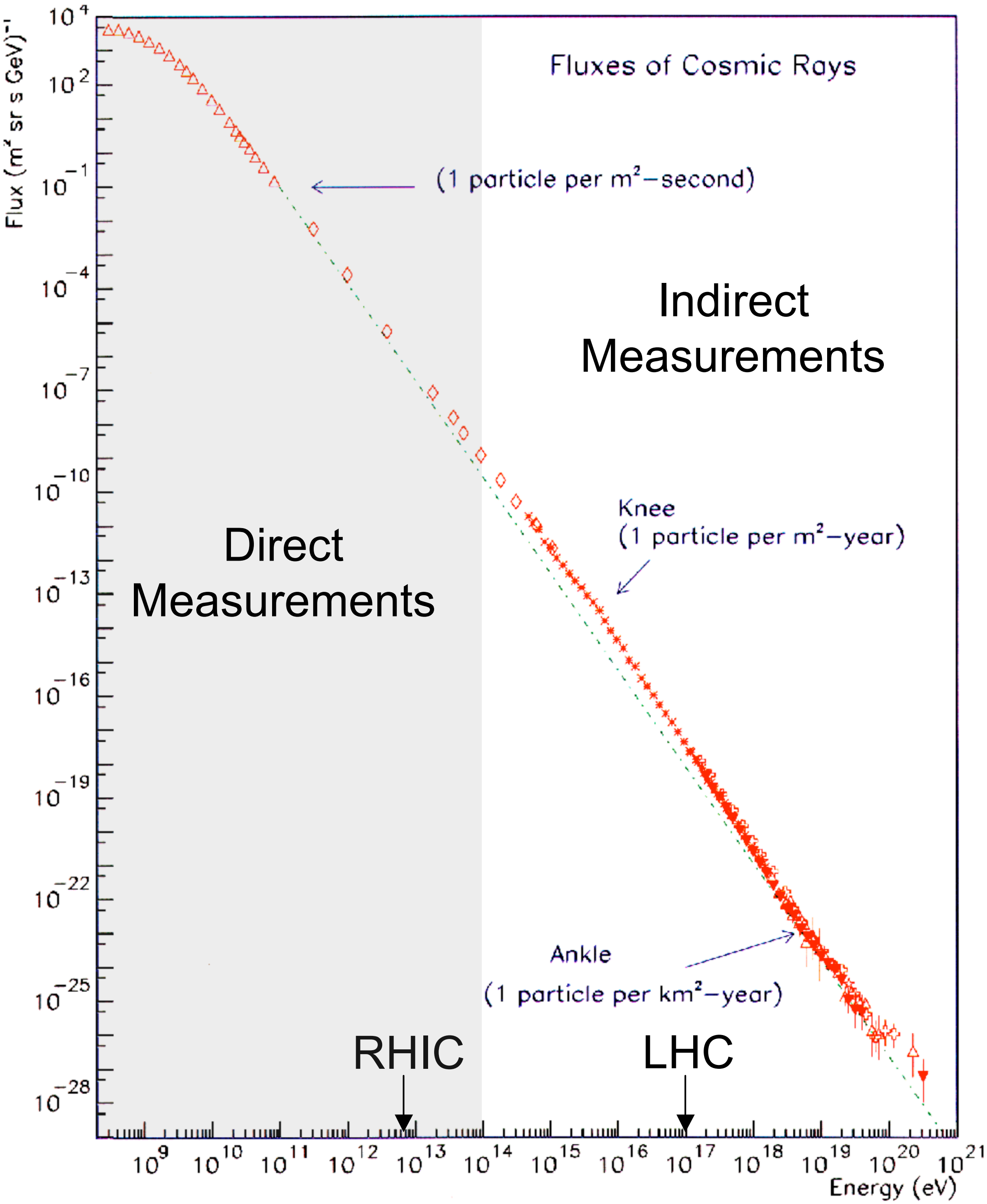
(INT Program 08-38W)

INSTITUTE FOR NUCLEAR THEORY

Lisa Gerhardt
April 14, 2008

Workshop Goal

- Bring together cosmic ray and nuclear physicists to discuss current understanding of high energy nuclear interactions
  - Two radically different approaches to same goal: better understanding of the universe by studying nuclear interactions
  - Two of the largest, most sensitive apparatus ever: Auger and LHC



Cosmic Rays

Spectrum falls as $E^{-2.7}$

Main features: knee and ankle

Origin uncertain:

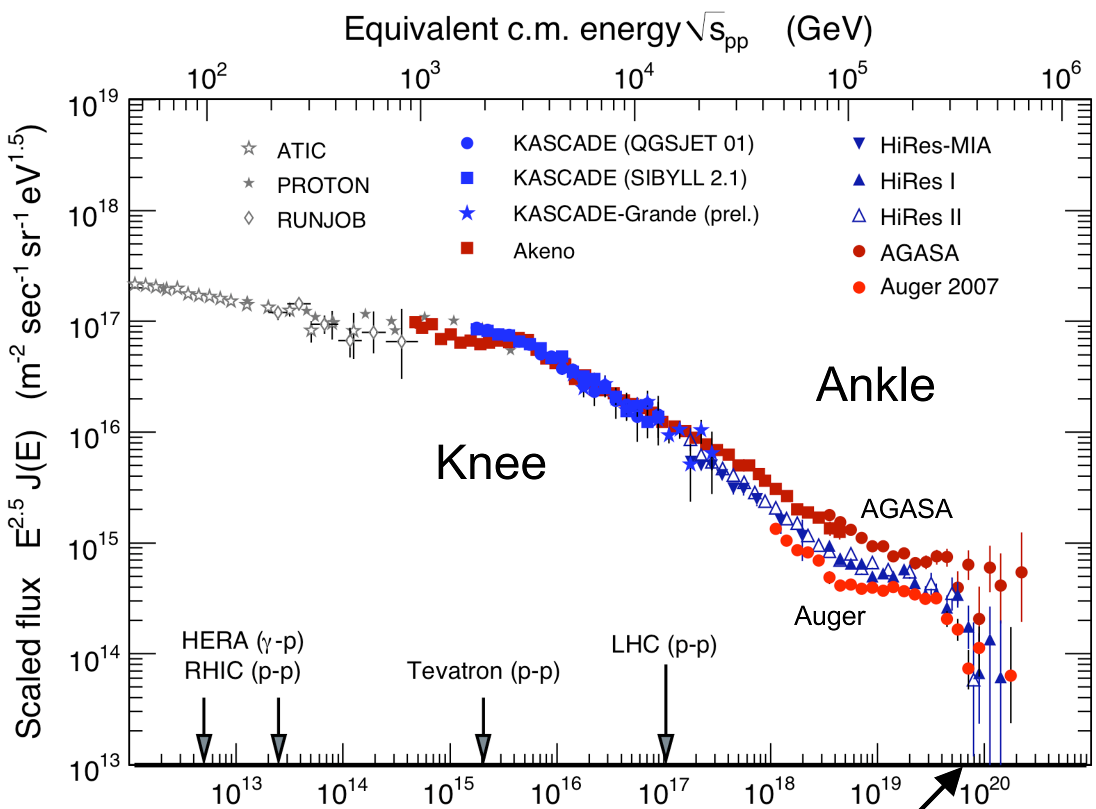
Supernova Remnants up to ~10^{16} eV

Beyond that, likely extragalactic

- Active Galactic Nuclei, Gamma Ray Bursts

CRs bent by magnetic fields, and interact along the way

The Most Energetic in the World…



R. Engel

$$p + \gamma_{CMB} \rightarrow \Delta^{+} \rightarrow \pi^{+} + n$$

Suppresses flux

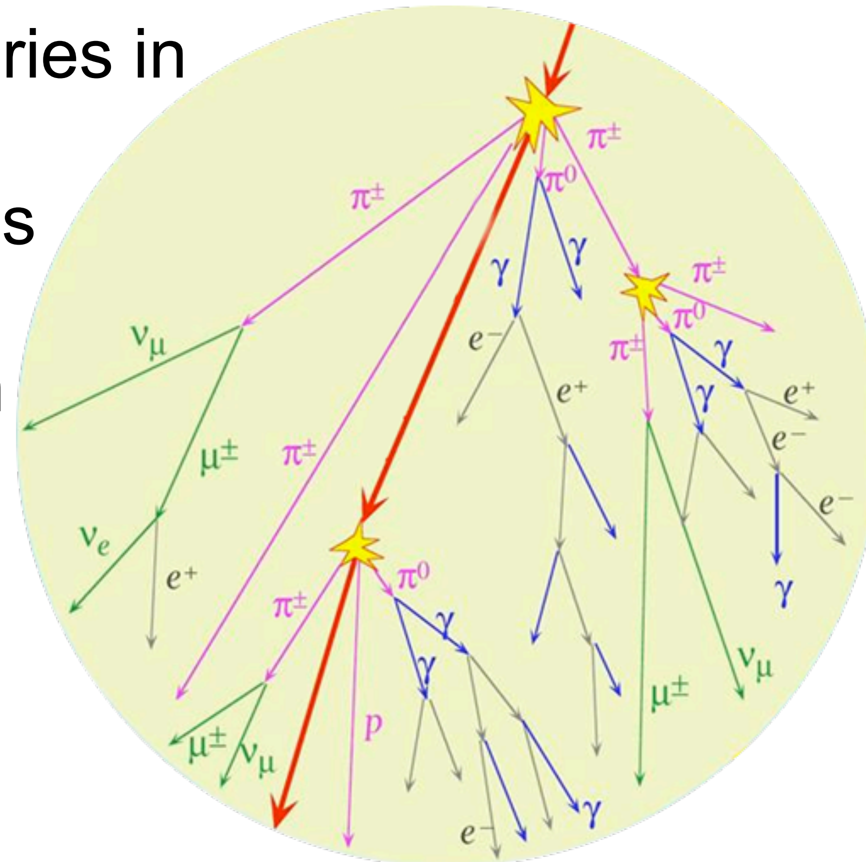
~1 particle/(km^2*yr): Need a massive detector to see highest energy cosmic rays

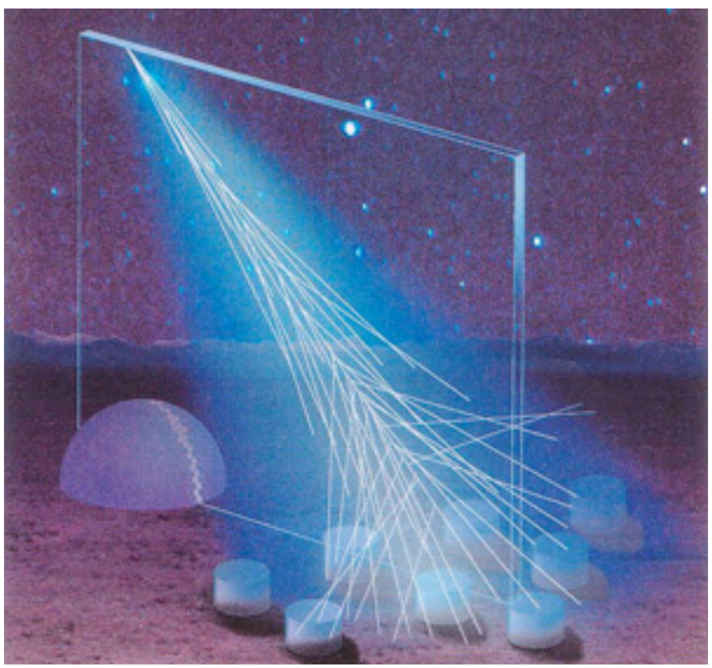
Auger: 3000 km^2, seen 81 cosmic rays with E > 4 x 10^{19} eV since 2004

Measured Quantities

Detect CRs through secondaries in their enormous cascades

Density and timing of particles relative to shower core: Electrons, muons, interaction height





Photons in atmosphere from Cherenkov effect and air fluorescence (excited nitrogen)

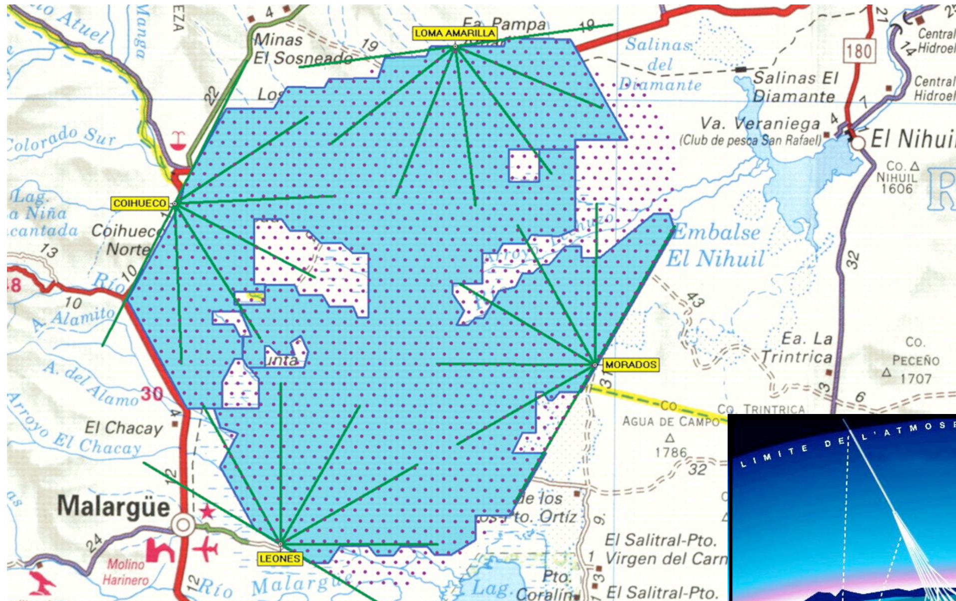
Detection Methods

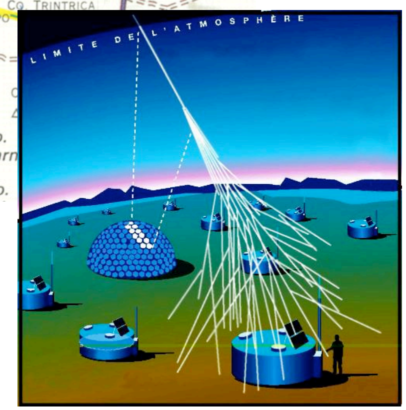
- Ground Arrays (AGASA, KASCADE)
  - Measure density of particles: N_μ, N_e
  - Strongly model dependent
  - Takes data 100% of the time
- Fluorescence Arrays (HiRes)
  - Tracks light of shower to measure energy
  - Model independent (still dependent on simulation to determine aperture)
  - Takes data ~10% of the time
    - Needs cloud-free, moonless nights and bright events
- Hybrid Arrays (Auger, TA)
  - Both ground and fluorescence
  - Can self-calibrate energy scale

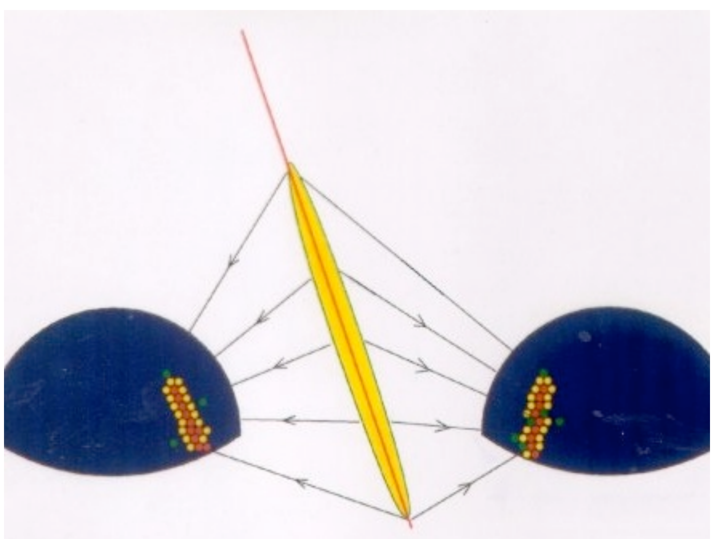
CR Detectors: Past and Present

Auger

- Collection area ~3000 km^2
- Fluorescence and ground array
- Taking data since 2004
- Energy threshold ~10^{18} eV





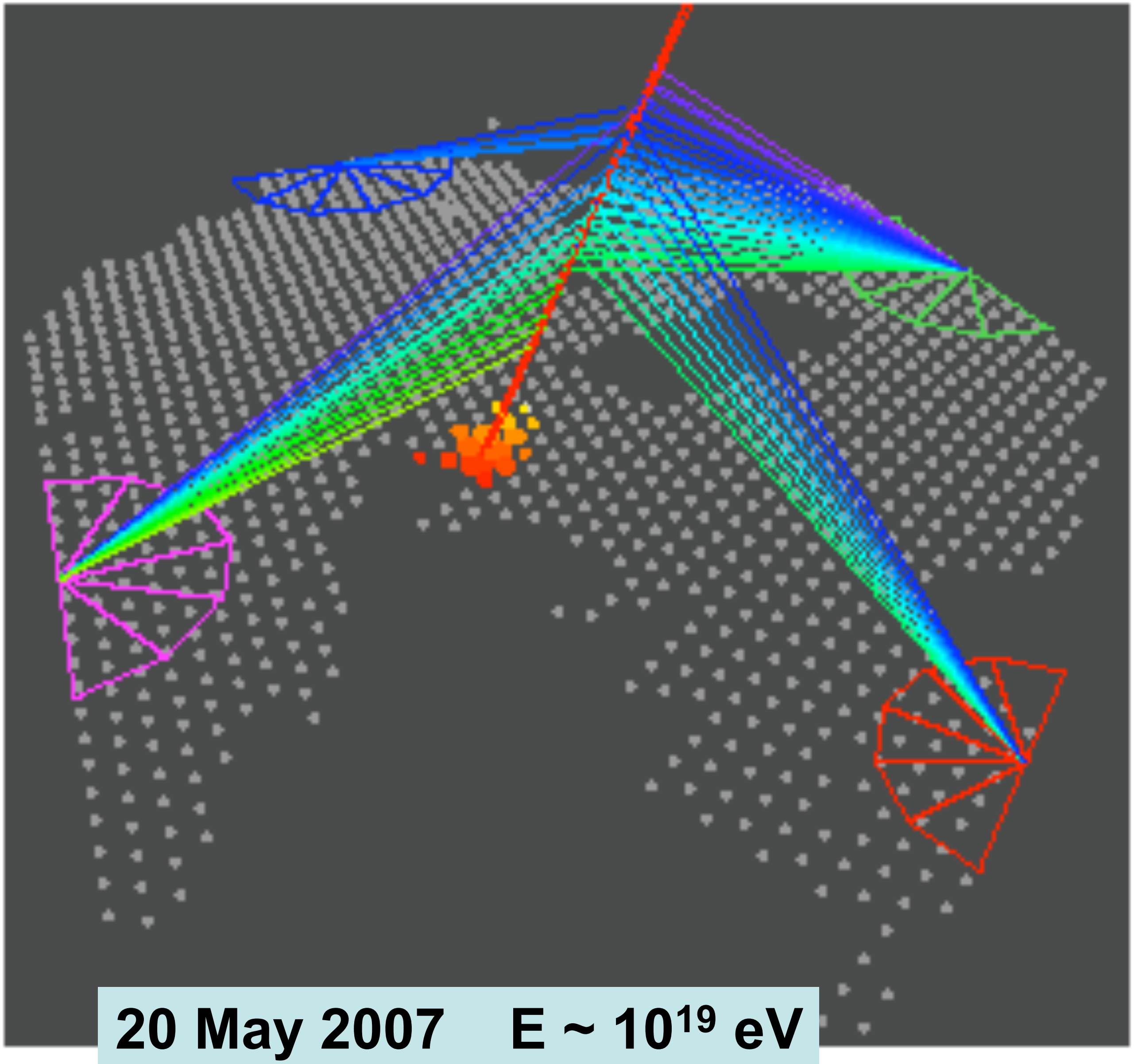


HiRes

- Fluorescence array
- Energy threshold ~10^{17} eV
- Took data from 1997 to 2006
- Highest energy CR so far 3.2×10^{20} eV

Many Others: AGASA, Kascade, Akeno,…

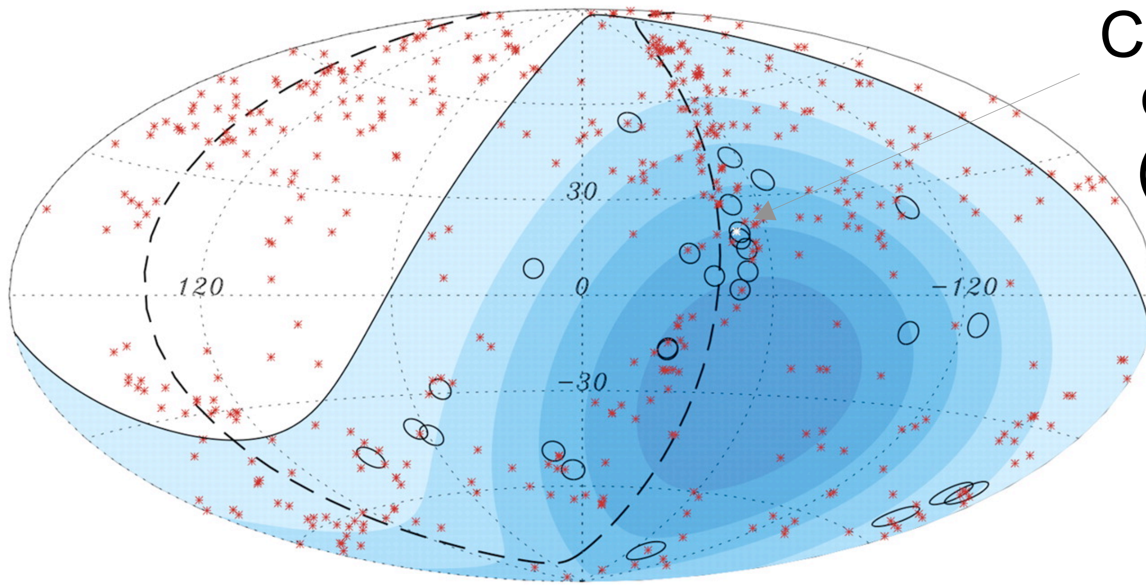
Auger: hybrid detector



J. Neto

First hybrid, 4-fold coincident event seen last May (4 FD and 15 SD)

Highest Energy CRs Point to AGNs?



- 20 of 27 Auger events with $E > 6 \times 10^{19}$ eV are within 3.1 degrees of an AGN less than 75 Megaparsecs away (244 million light years): a 3σ significance

Implications of CR Correlation

- CRs are charged, so will be bent by magnetic fields

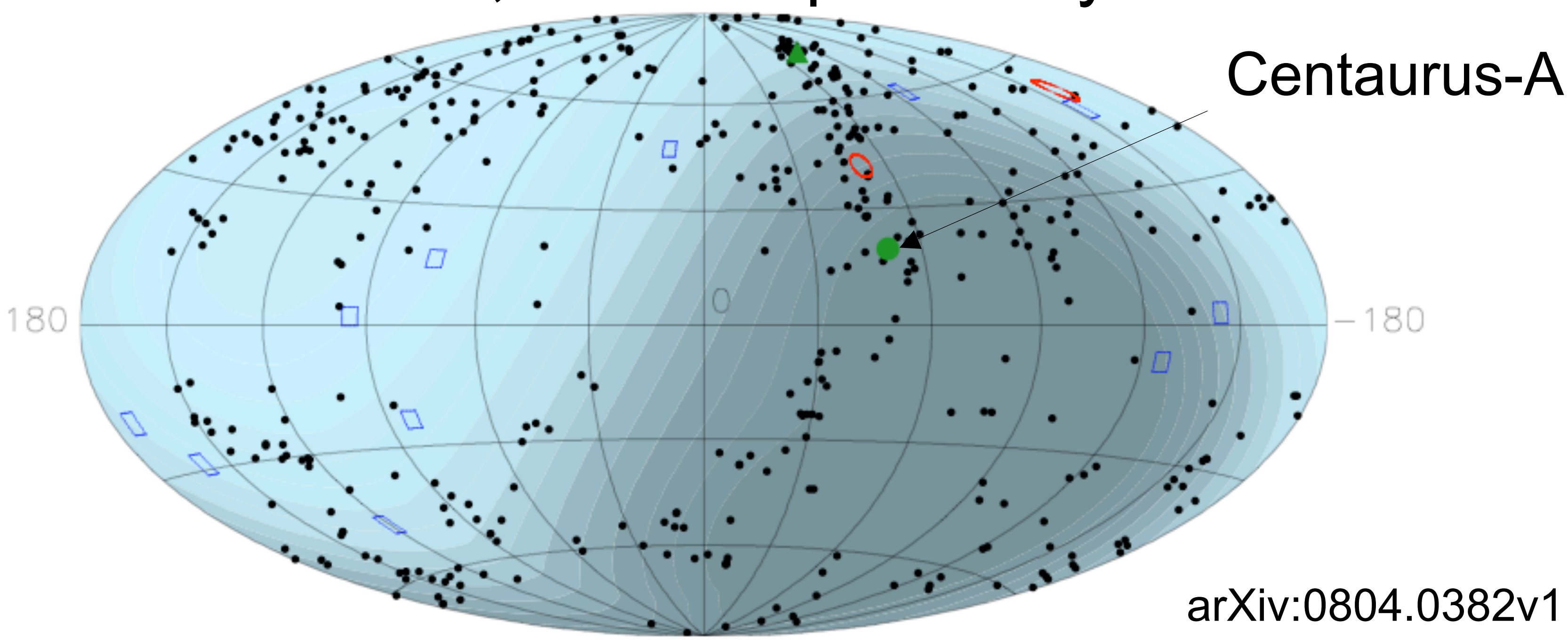
$$\delta \approx 2.7^\circ \times Z \times \frac{60\ \mathrm{EeV}}{E} \left| \int \left(\frac{dx}{\mathrm{kpc}} \times \frac{B}{3\mu\mathrm{G}} \right) \right|$$

arXiv:0712.2843

- Auger correlation within 3.1°, implies the majority of the highest energy cosmic rays are protons

Or not?

- HiRes has a comparable dataset to Auger, but they do not see a correlation with AGNs (or anything else)
  - 13 events w/energy > 5.6×10^{19} eV, 2 correlations, with 3 expected by chance



arXiv:0804.0382v1

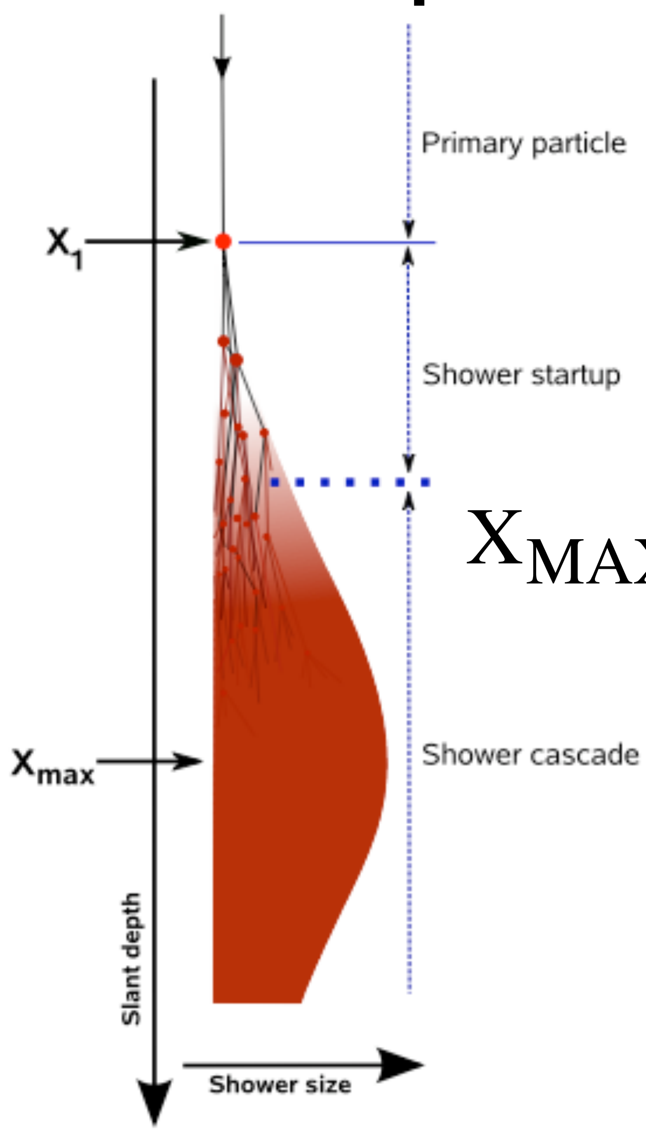
Current Status

- Disagreement between experiments: correlation - Auger and HiRes
- Examine additional experimental variables

Another Measurement: Composition

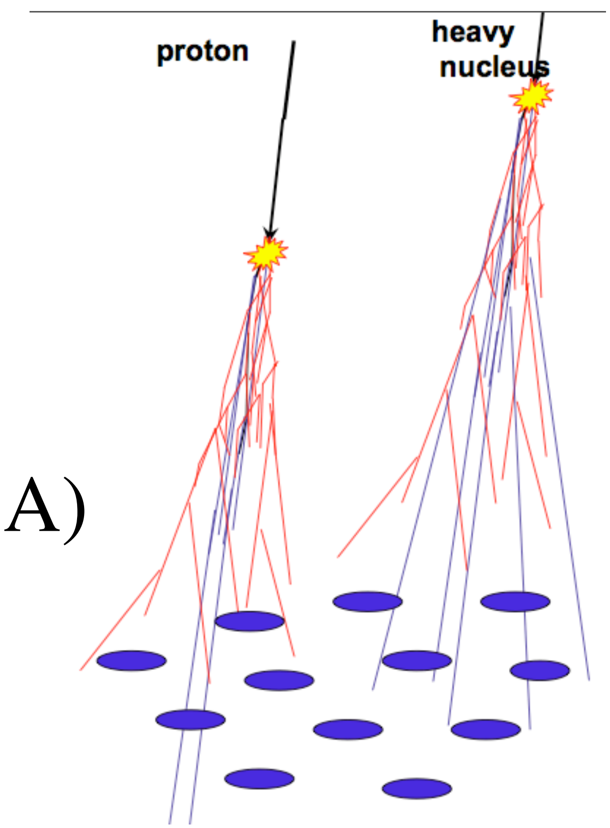
- The energy per nucleon changes with composition
  - 10^{17} eV proton: 1 nucleon
  - 10^{17} eV iron: 56 nucleons, each with ~2 x 10^{15} eV
- Effects development of shower in the atmosphere
  - Shower from particle of mass **A** and energy **E** is superposition of **A** showers with energy **E**/**A**
  - Changes ratio and energy of secondary particles

Composition Measurements



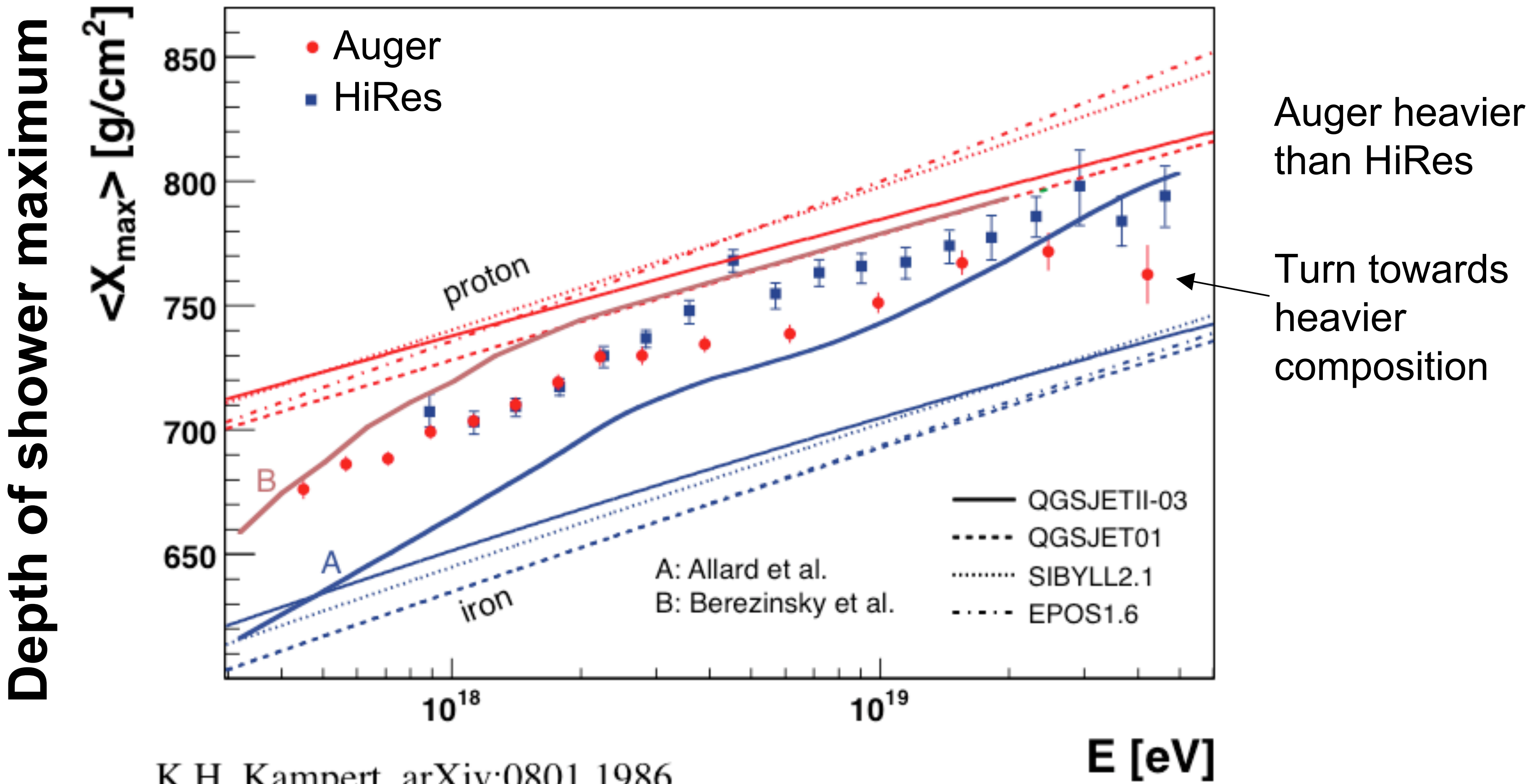
R. Ulrich

$$X_{MAX} \propto \ln(E / A)$$



X_{max}, ratio of electrons to muons, energy and number of muons and electrons are all composition dependent

ICRC Results (2007)

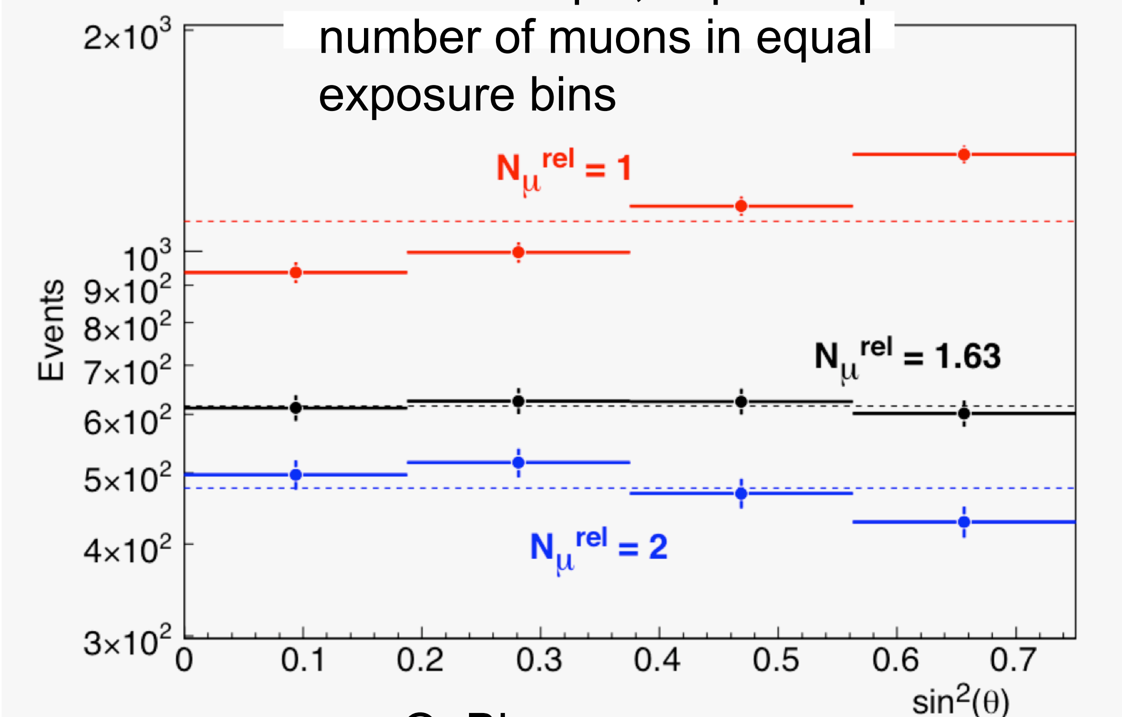


K.H. Kampert, arXiv:0801.1986

Auger and HiRes see X_{max} distributions consistent with a mixed composition, in disagreement with Auger coincidence results.

N_μ Discrepancy

Lower energy cosmic ray flux is isotropic, expect equal number of muons in equal exposure bins



O. Bigas

Simulations underestimate the number of muons at high energies by a factor of ~1.5. Similar dearth of muons seen at lower energies.

Current Status

- Disagreement between experiments: correlation - Auger and HiRes
- Disagreement within experiments: Auger - correlation and X_{max}
- Disagreement between experiment and simulation for shower parameters
  - N_{μ}, lateral distribution of electrons
- A better understanding of interaction models will help resolve these issues

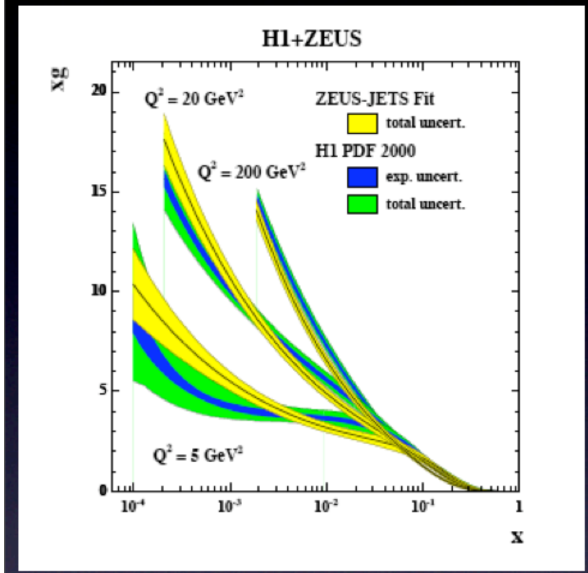
Interaction Models

- Relationship between observables and composition/energy is dependent on the models used to characterize the cosmic ray showers
  - Based on theoretical calculations bounded by accelerator results
- CRs test interaction models in the forward physics region
- Extrapolate accelerator results to better understand highest energy CR data

Key Variables of Interaction Model

- p - Air cross section: Rate, X_{max}
- Distributions of secondary particles
  - Neutral pions: N_e
  - Charged pions: N_μ
  - Baryon-Antibaryon pairs: N_μ
- Extrapolate these (and others) to CR energies from accelerator measurements

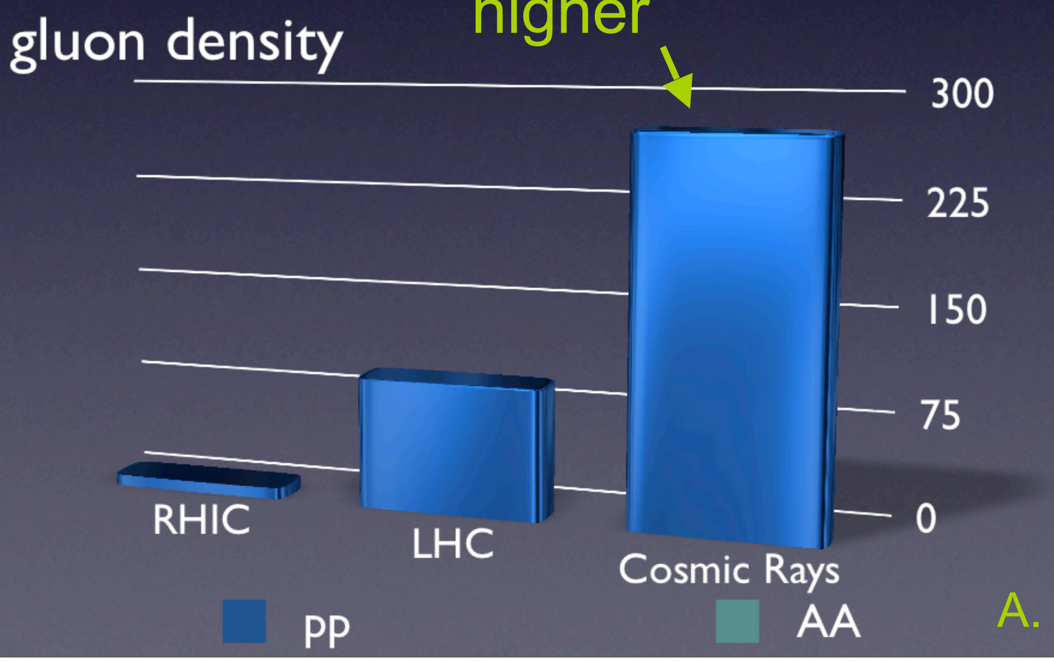
Estimates of gluon density



Extrapolation of gluon density
to various energies

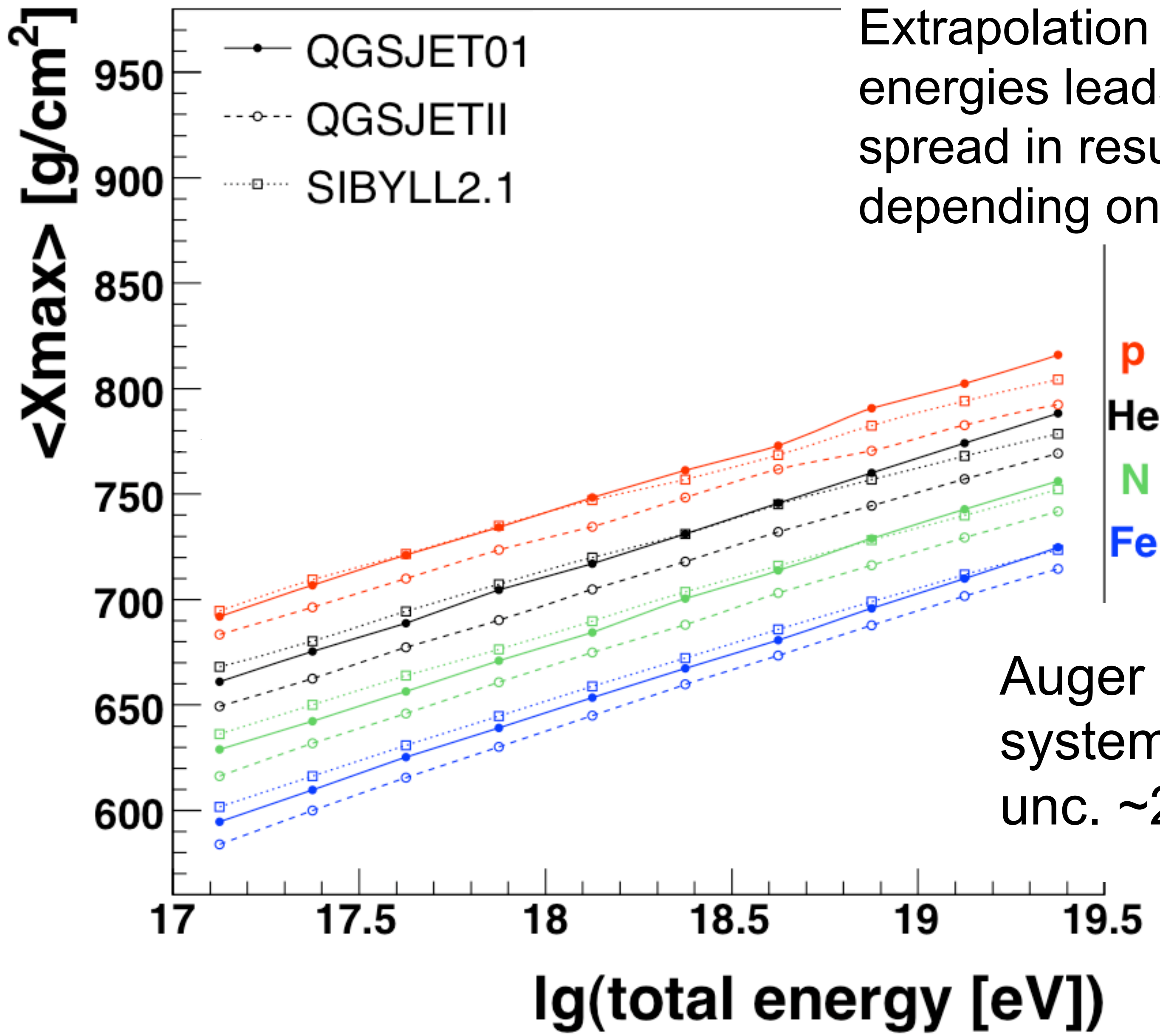
Scale $Q^2 = 5\ \mathrm{GeV}^2$ $x \sim \dfrac{Q^2}{s}$

factor of ~4
higher



- Extremely small x probed at Cosmic Ray energies: extrapolation over 5 orders of magnitude in x

A. Stasto

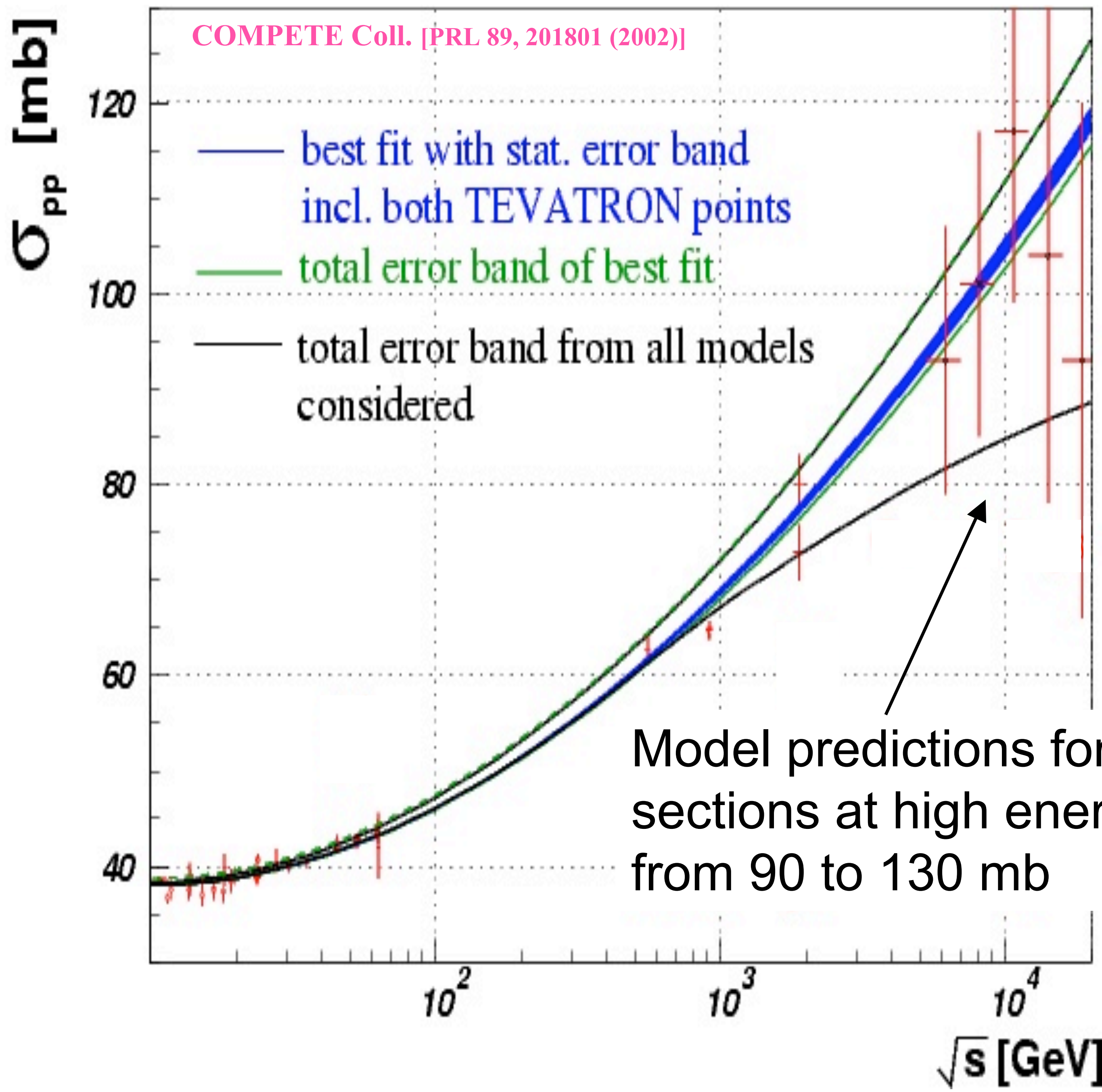


Extrapolation to high energies leads to a large spread in results depending on model used

Auger systematic unc. ~20 g/cm^2

Similar spread seen in other observables

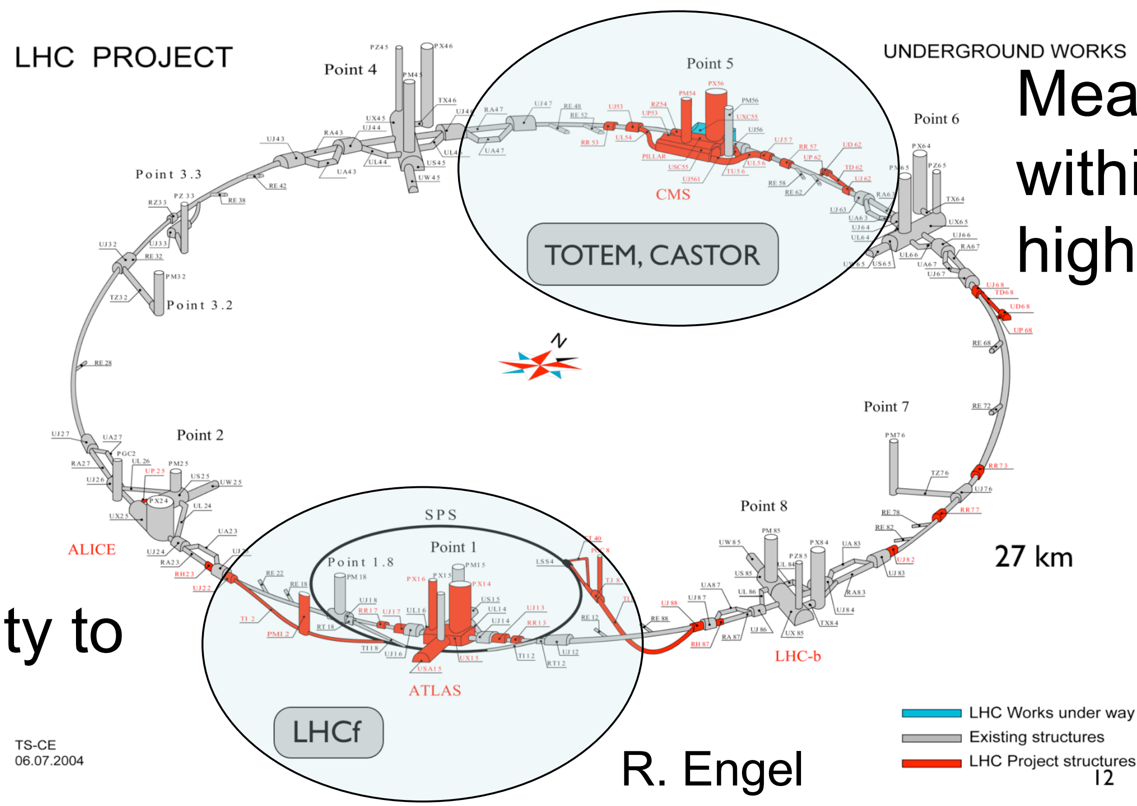
M. Unger



Model predictions for cross sections at high energy vary from 90 to 130 mb

Forward Physics at LHC

- LHC will reach CM energies of 14 TeV
- Several additions planned to increase data at high rapidity and low x

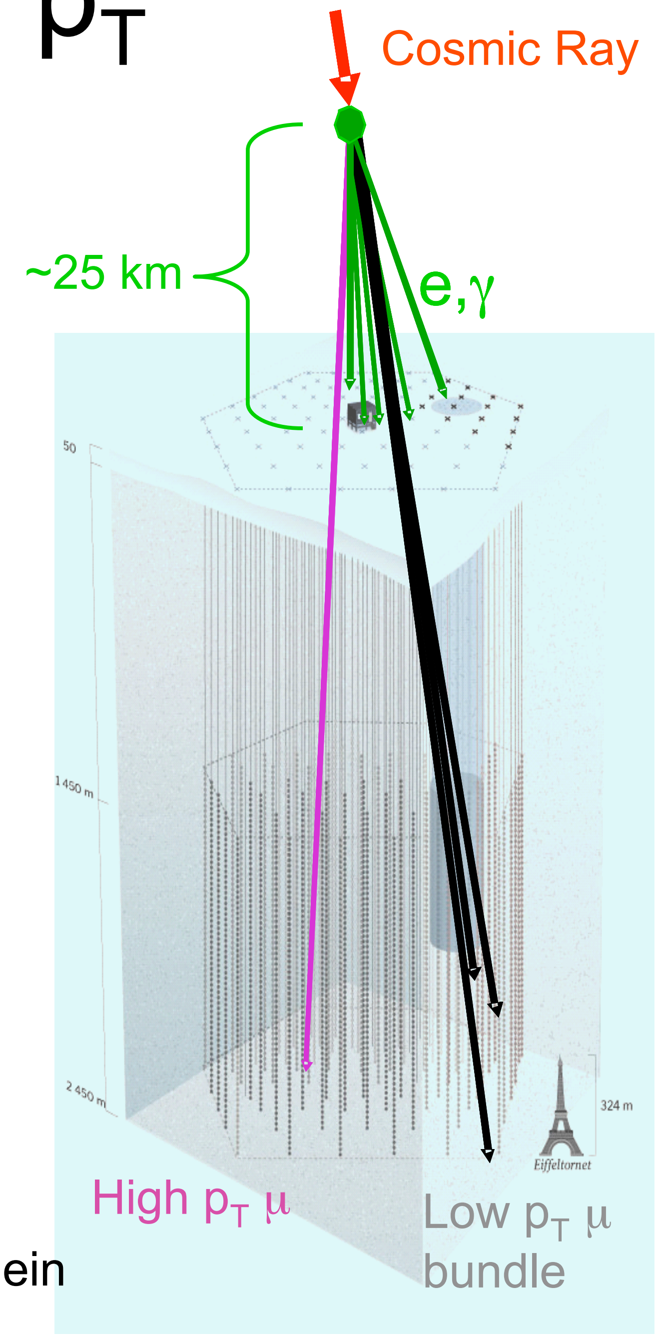


Measure σ_{pp} to within 1% at highest energies

Extend rapidity to CR region

An Alternative: High p_T Muons

- Muons with a large transverse momentum produced early in the shower
  - Spectrum is sensitive to composition
- Detect shower energy and high p_T muon in IceCube

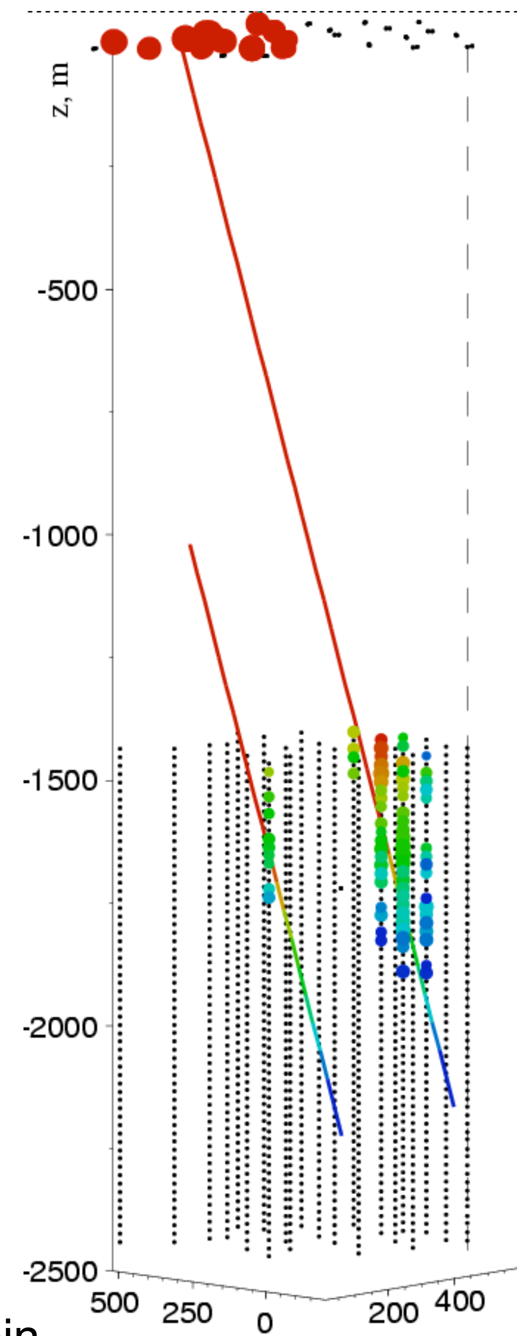


S. Klein

Proof of Principle – an IC22 event

- 11 IceTop surface stations hit
- 96 InIce DOMs hit
  - 84 on 4 strings near the extrapolated shower direction
  - 12 on another string, about 400 m away.
- Event from May 23, 2007, found in a search of 4 days data
- An independent method to measure composition

IceCube Collaboration, 2007 ICRC

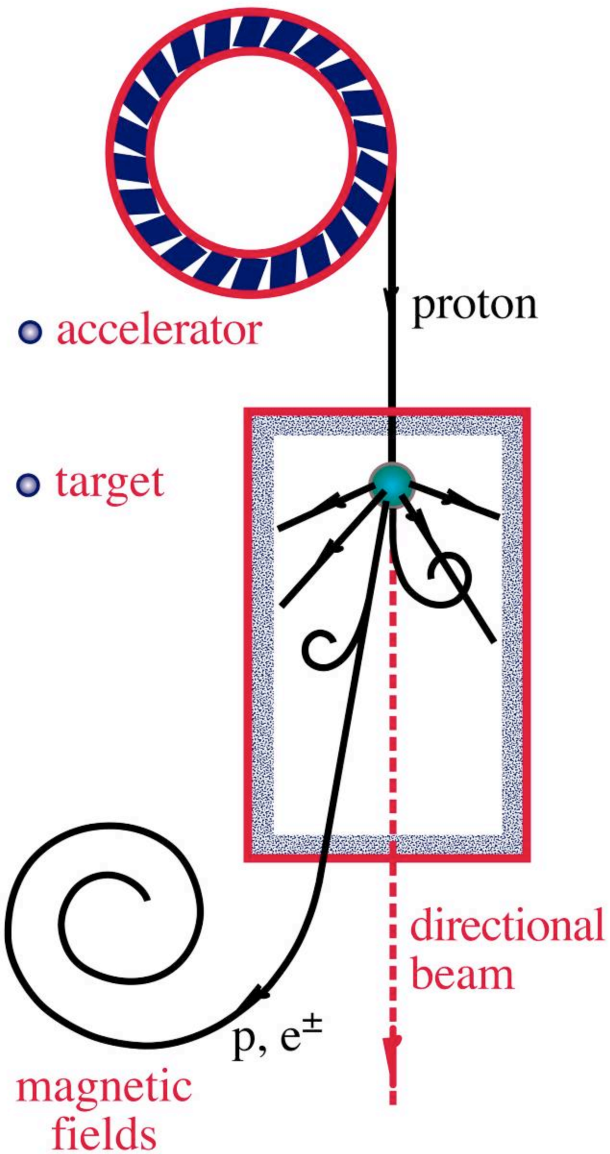


S. Klein

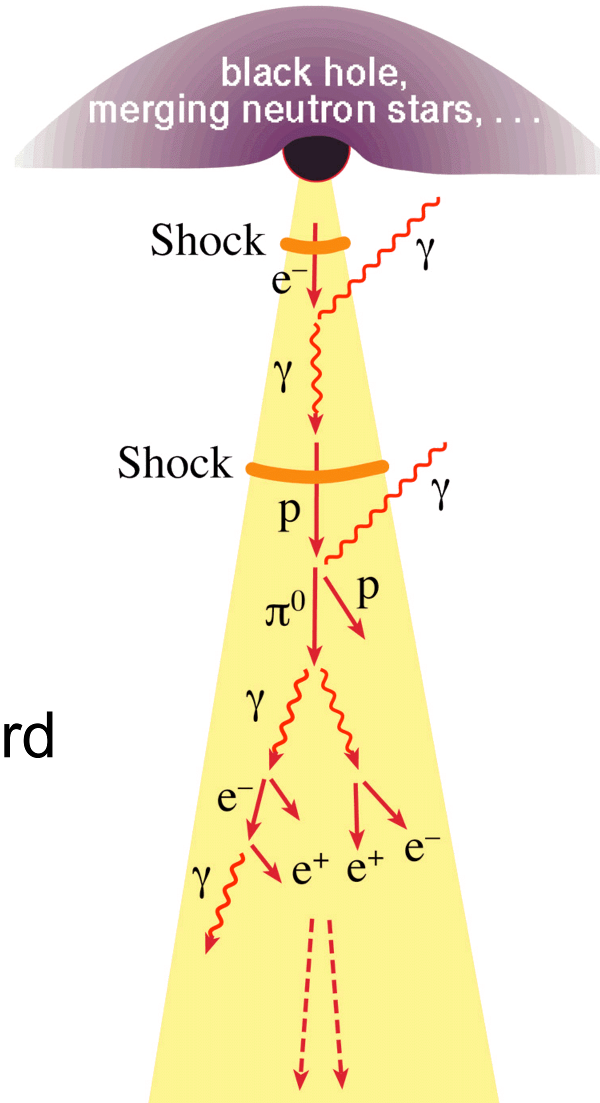
Conclusion

- Many unresolved questions about highest energy cosmic rays
  - Composition, origin, shower constituents
- Accelerator measurements essential for accurate modeling of shower parameters and understanding of the universe
- Cosmic ray measurements can help constrain accelerator results

Cosmic Accelerators



Effectively a fixed target geometry. Particles produced in the far forward region (high rapidity).



High Rapidity, Low x

RHIC: rapidity ~ 4

$x \sim 10^{-4}$

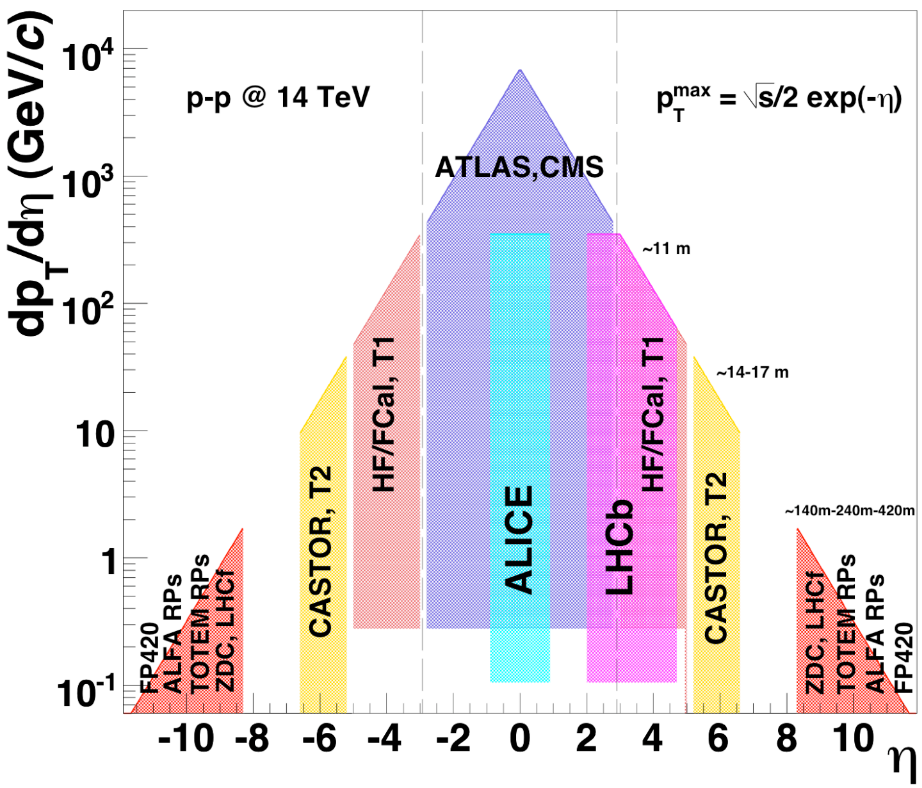
LHC: rapidity ~ 6-10

$x \sim 10^{-6}$

CRs: rapidity ~ 8

$x \sim 10^{-8}$

Phase space coverage



R. Engel

Detection of Highest Energy CRs

- Odds of catching one high energy cosmic ray in a balloon-born apparatus are about 1 in 10 million
  - Roughly as likely as winning the state lottery (and about as expensive)
- Look for secondaries from extensive showers of cosmic rays in the atmosphere with massive ground arrays
  - Much greater exposure time and collection volume
  - But must infer composition, direction from the secondaries
  - Highly dependent on simulation

Model Independent Parameters (CIC)

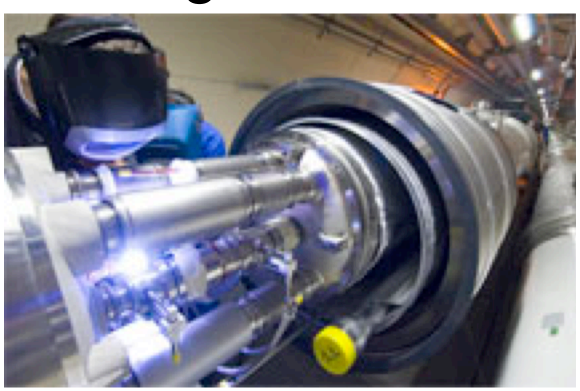
- Should get equal number of events in equal exposure bins
  - Corrected for detector acceptance
- Calculate the number of events in each bin above a given energy and number of muons
- Divide by “true” (simulated) number of muons

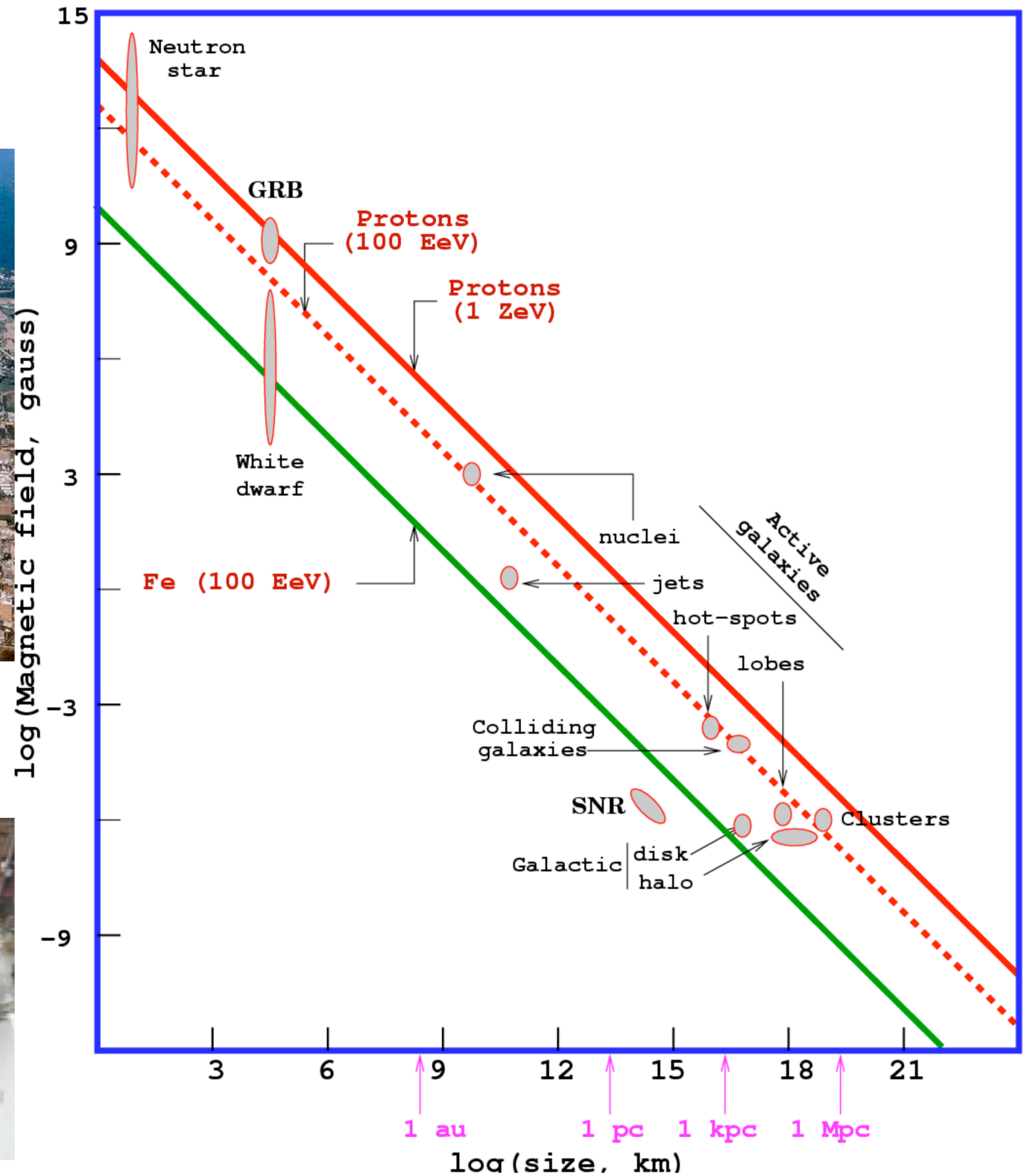
Sources of Highest Energy Cosmic Rays

Requirements:

Large size (confinement)

Powerful Magnetic Field

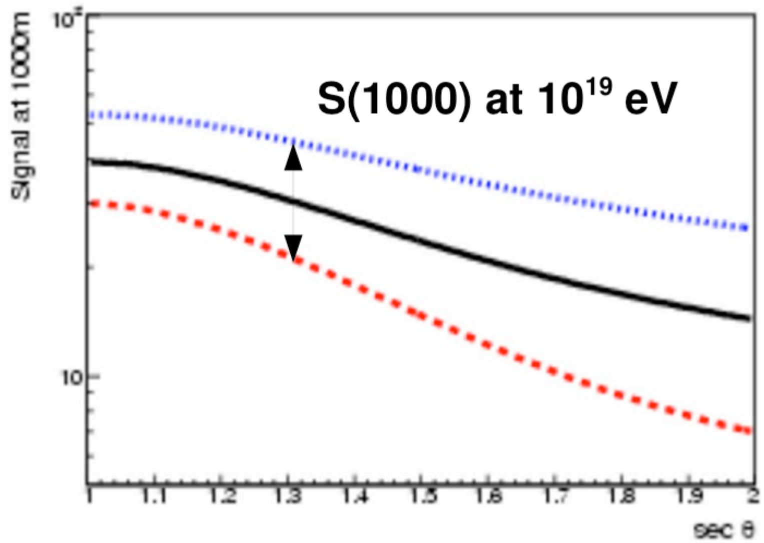


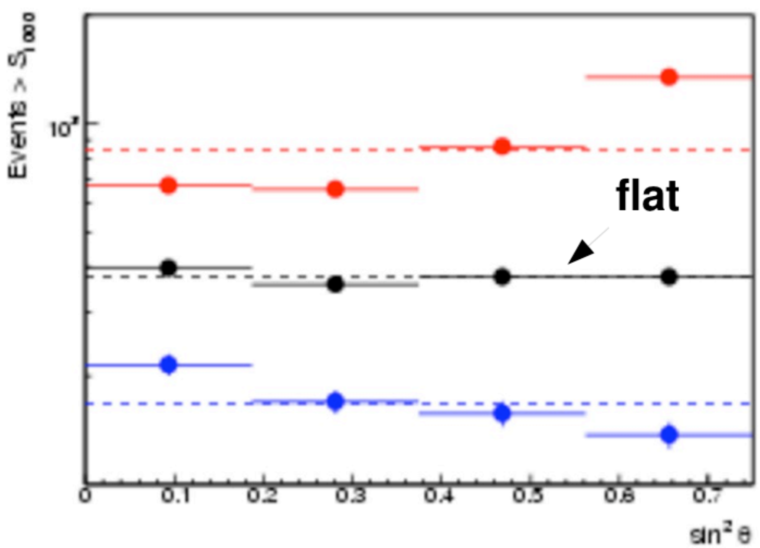


Constant intensity method

- $N_\mu = 1.0$: right ...

Energy fixed at 10^{19} eV





Signal at 1000m vs sec θ

--> "attenuation curve"

N_{events}(> S) in equal exposure bins ($\sin^2\theta$)

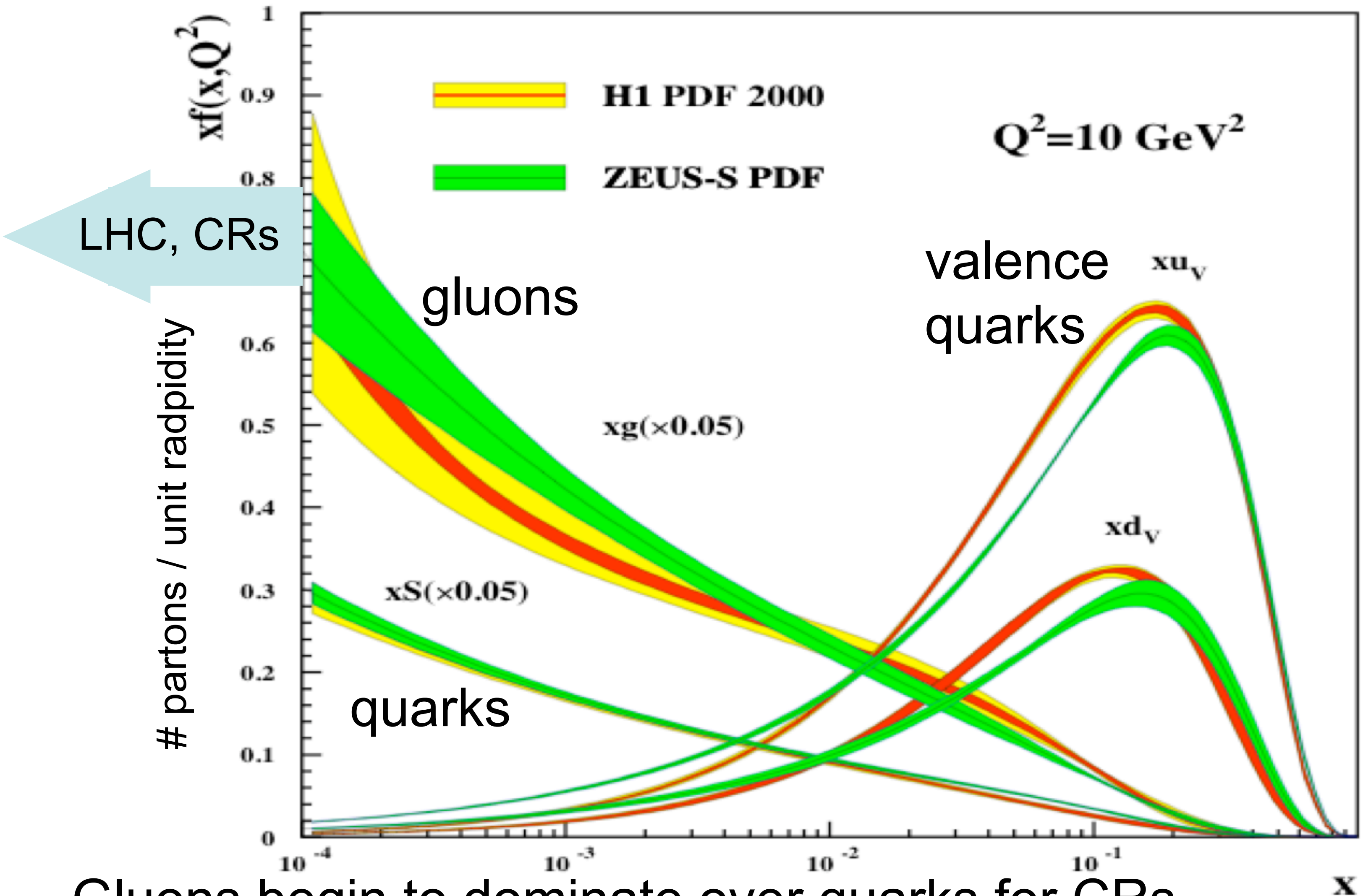
Impact of the uncertainty of hadronic interaction features on air showers

EAS observable	cross section	multiplicity	inelasticity
$\langle X_{\mathrm{max}} \rangle$	**strong**	**strong**	**strong**
$\mathrm{RMS}[X_{\mathrm{max}}]$	**strong**	weak	none(?)
$\langle \log_{10}(N_{\mathrm{e}}) \rangle$	**strong**	**strong**	**strong**
$\mathrm{RMS}[\log_{10}(N_{\mathrm{e}})]$	**strong**	**strong**	weak
$\langle \log_{10}(N_{\mu}) \rangle$	weak	some	**strong**
$\mathrm{RMS}[\log_{10}(N_{\mu})]$	weak	weak	none(?)

R. Ulrich

Three Main Interaction Models

- SIBYLL
  - pQCD: Uses dual parton model with minijets, designed for extensive air showers
- QGSJET
  - Quark, Gluon and String Model with JETS, describes hadronic interaction by exchaning pomerons, includes jets for higher energy interactions
- EPOS
  - Includes elastic and inelastic parton ladder splitting, based on pp and dAu at RHIC

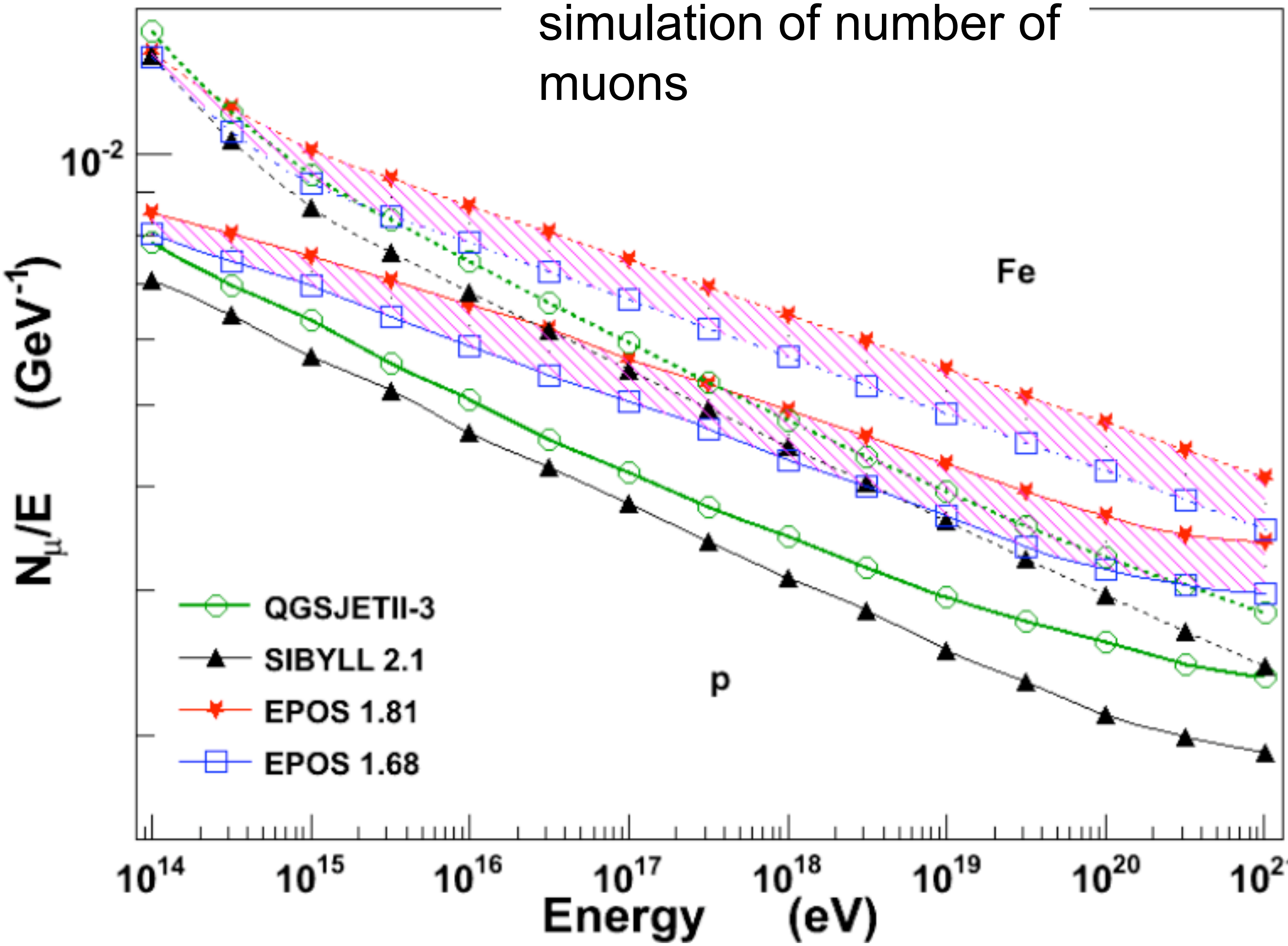


Gluons begin to dominate over quarks for CRs

J. Jalilian-Marian

Must start to worry about collective effects (minijets, nuclear shadowing of gluons)

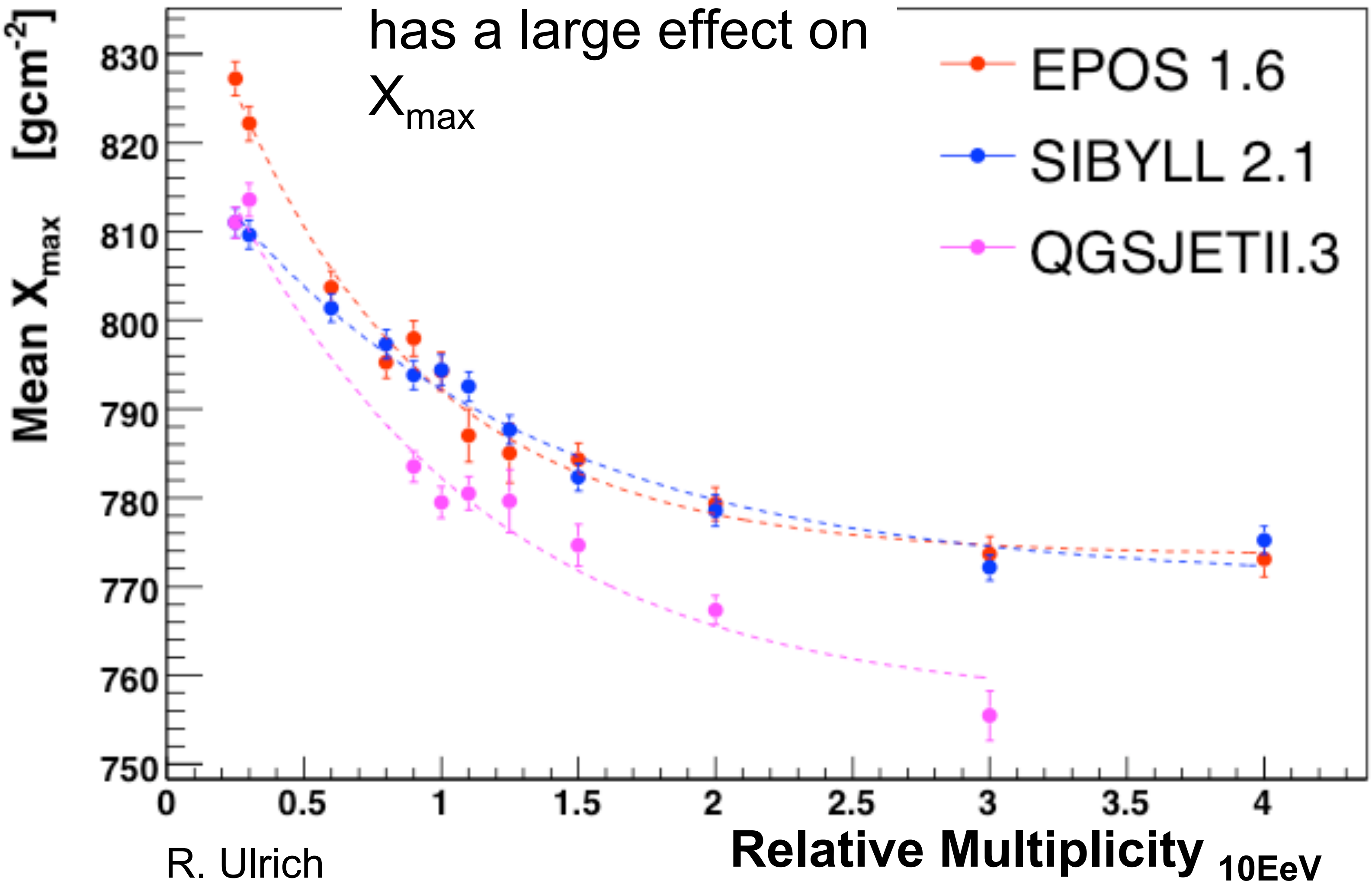
Similar spread seen in simulation of number of muons



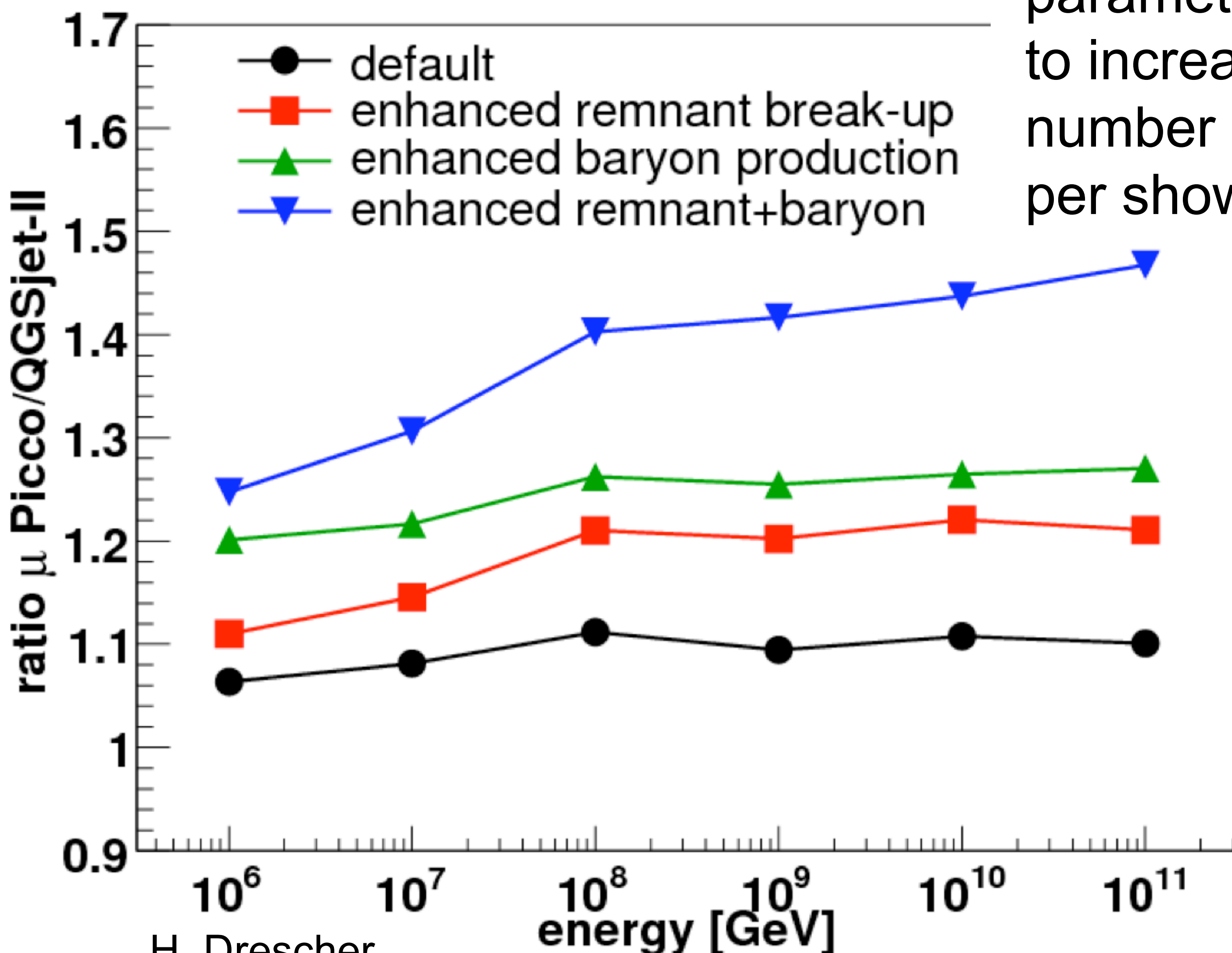
factor of 2

T. Pierog

Artificially modifying particle multiplicity has a large effect on X_{max}



R. Ulrich



H. Drescher

Can tune parameters to try to increase number of muons per shower

Widely shared expectation:

Interaction of the fast partons with nuclear media is determined by gluon thickness of media along the parton path for smallest x which the parton can resolve.

Compare central deuteron -gold collision at RHIC and p-air at b < 2 fm at GZK

$$\frac{\text{gluon density GZK p- air}}{\text{gluon density RHIC d Au}} = \left(\frac{14}{200}\right)^{1/3} \left(\underbrace{\frac{x_{min}(dA)}{x_{min}(p-air)}}_{10^5}\right)^{\omega}$$

$=4$ (using a conservative value of $\omega=0.2$)

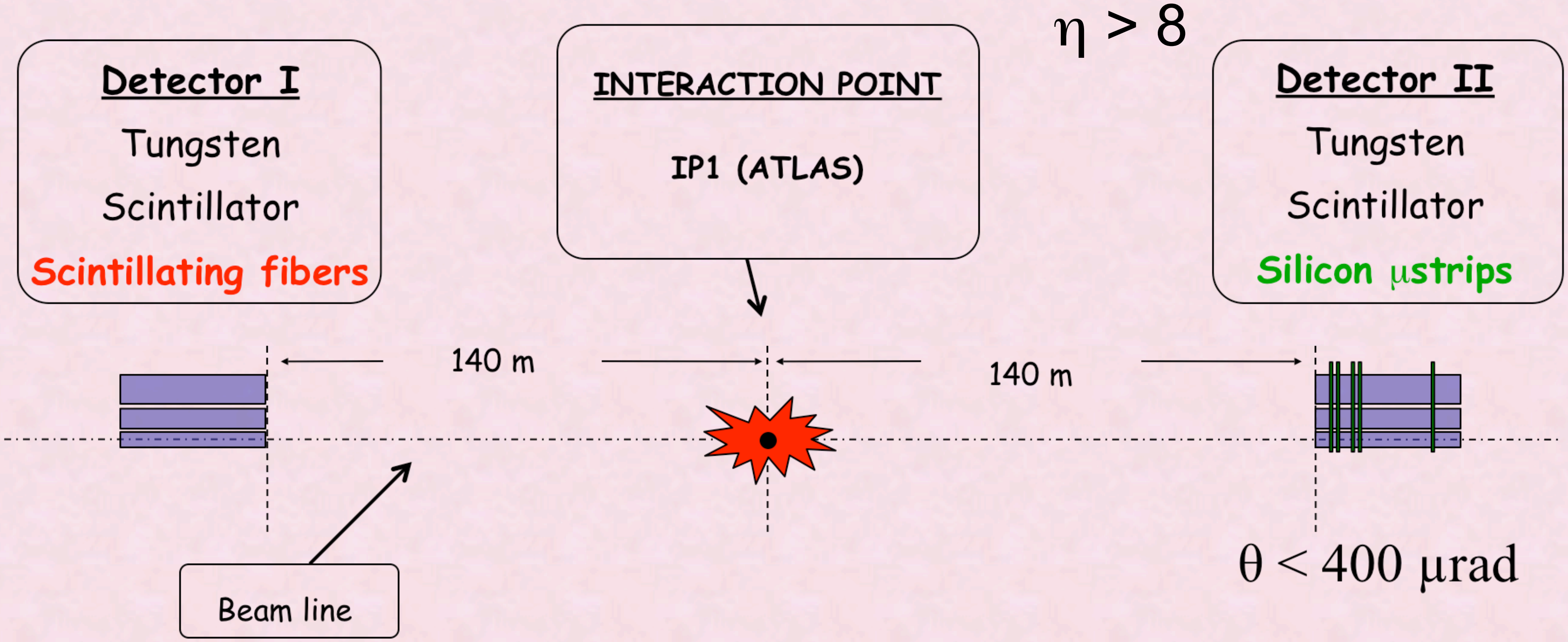
➠ **Stronger suppression of forward production at GZK than observed at RHIC**

M. Strickman

gluon density GZK p-air ~ gluon density LHC p Pb

LHCf: detectors on both sides of IP1

Sample CR rapidity region: $\eta > 8$

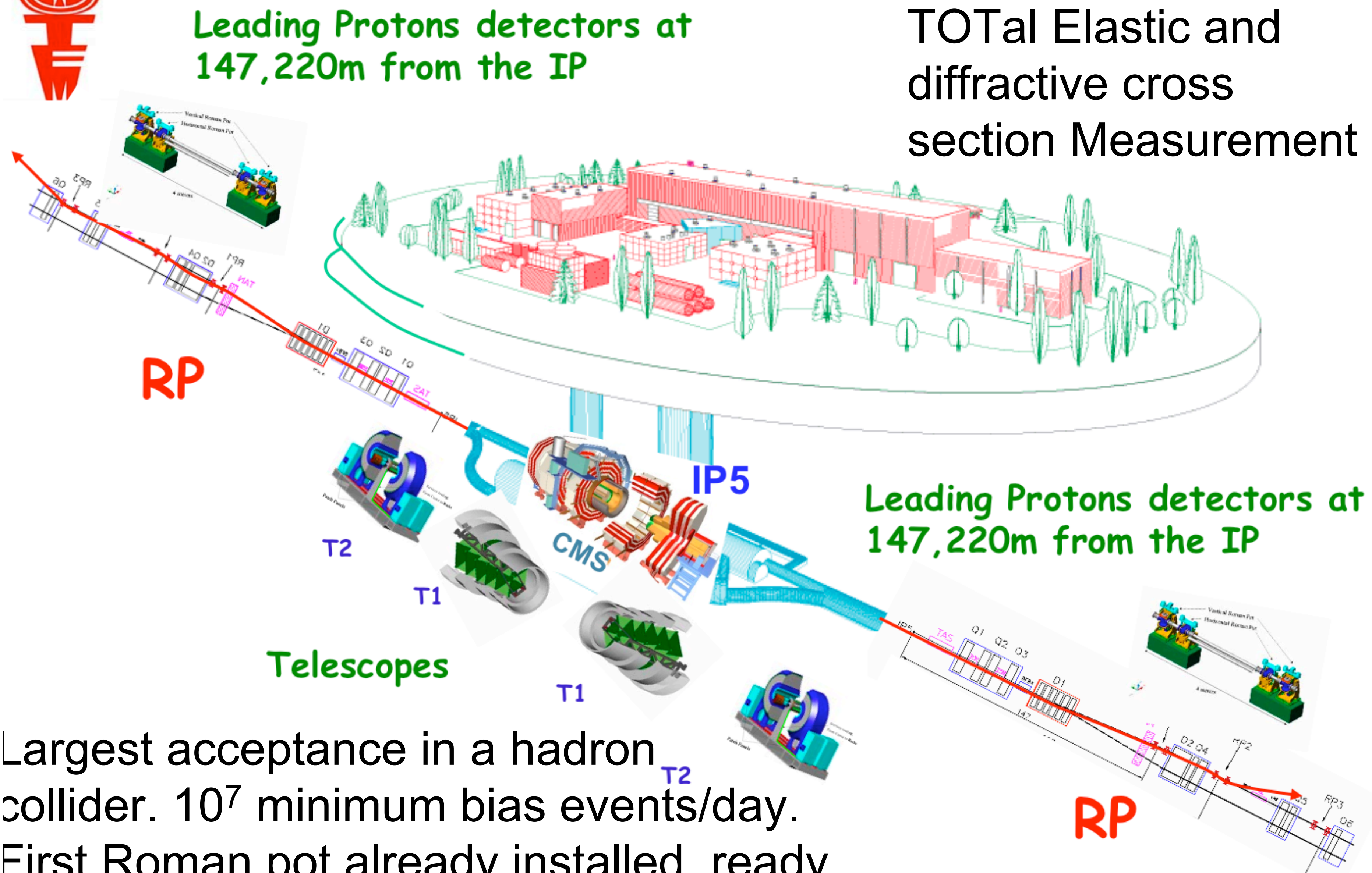


$\theta < 400\ \mu\text{rad}$

Detectors should measure energy and position of γ from π^0 decays → e.m. calorimeters with position sensitive layers

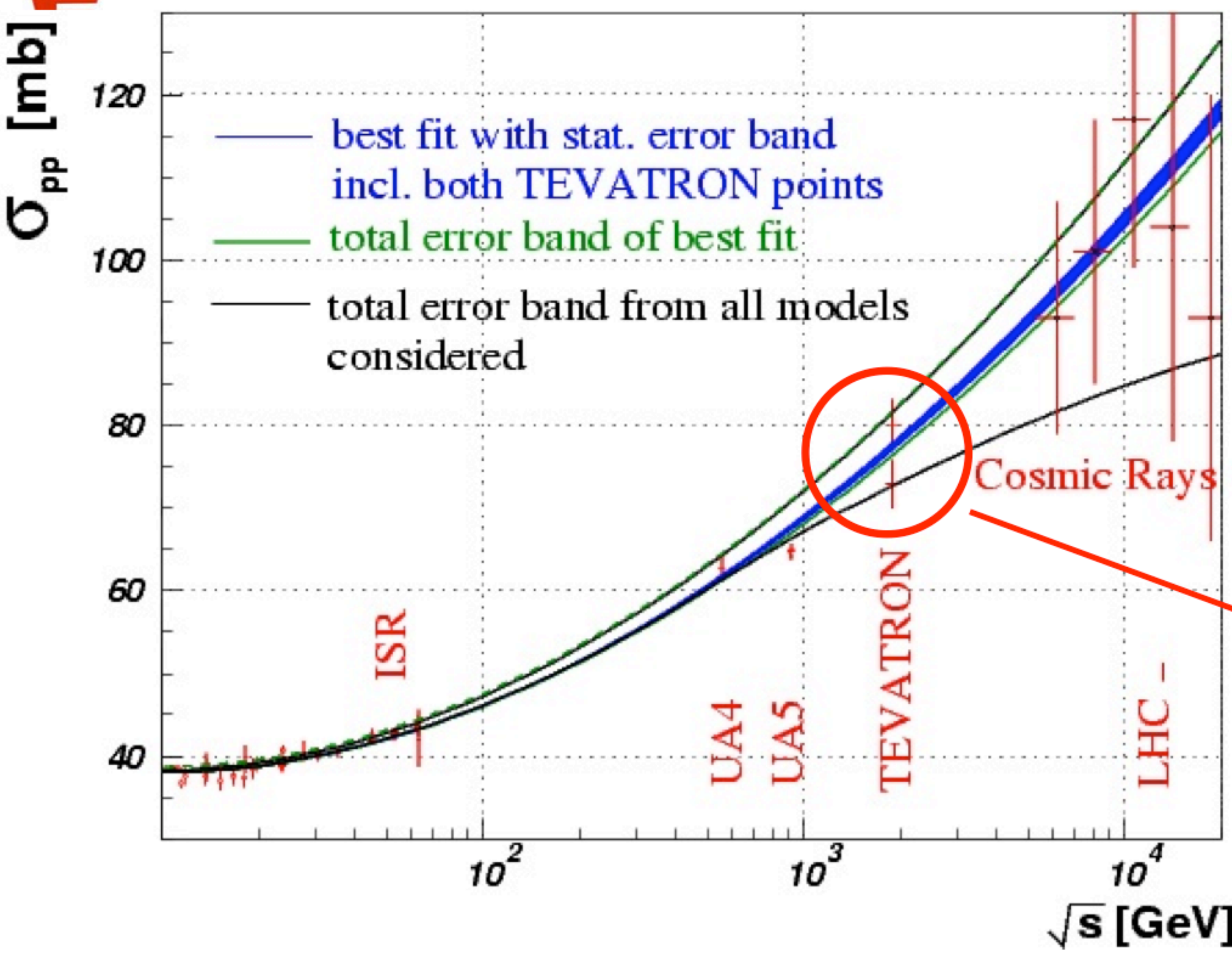
Experimental layout

TOTal Elastic and diffractive cross section Measurement



Largest acceptance in a hadron collider. 10^7 minimum bias events/day. First Roman pot already installed, ready to take data at LHC start

pp total Cross-Section



Current models predictions: 90-130 mb

Aim of TOTEM: ~1% accuracy (~1 mb)

Sample high η

E811-CDF disagreement $\approx 2.6\sigma$ (~10 mb)

COMPETE Collaboration fits all available hadronic data and predicts:

LHC: $\boxed{\sigma_{tot} = 111.5 \pm 1.2 \begin{array}{l} +4.1 \\ -2.1 \end{array} \text{ mb}}$

[PRL 89 201801 (2002)] Cudell et al.